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Analysis of combinations of glazing properties to improve economic efficiency of buildings

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ABSTRACT

The ideal combination of low solar heat gain coefficient (SHGC) and high visible transmittance (VT) to maximize energy efficiency of buildings is difficult to achieve because the two quantities have a trade-off relationship. This study analyzed the combination to reduce the energy consumption of office and residential buildings, then proposed a guideline to improve the economic efficiency based on energy cost compared with initial investment cost. First, the glazings used in South Korea were investigated and the possible combinations of SHGC and VT were classified. Then the energy consumption of each combination was quantified. As SHGC decreased and VT increased, energy consumption decreased in the office building, but not in the residential building. Next, the economic efficiency was analyzed for each combination. The efficiency of the office building can be improved by weighting to favor energy consumption over investment cost. While due to nonlinear relationship of energy consumption between SHGC and VT in the residential building, the increased investment cost and decreased energy cost should be compared. This study can contribute to decision-making in ambiguous conditions, such as when the energy cost decreases but investment cost increases.

1. Introduction

The building sector is large consumer of energy and natural resources (Motuzienė et al., 2016). Especially, windows increase heat loss when applied to a building envelope (Kontoleon, 2015) and are responsible for approximately 20–40% of the total heat loss of residential buildings (Hee et al., 2015) and 13–35% of office buildings in South Korea (Jang et al., 2007). To decrease energy consumption, glazing that has low thermal transmittance and low solar heat gain coefficient (SHGC) but high visible transmittance (VT), have been developed. These properties are critical from the perspective of energy efficiency (Chen et al., 2017). However, SHGC and VT have a trade-off relationship, which is represented using the Light-to-Solar-Gain ratio (LSG) (Fathoni et al., 2016). The SHGC influences cooling energy and indicates the amount of solar heat that passes through the glazing (Lee et al., 2012). VT influences lighting energy and indicates the amount of natural light that can pass through glazing (Sharp et al., 2014).

Although many previous studies have analyzed energy consumption and economic feasibility according to glazing properties such as thermal transmittance, SHGC, and VT, few studies have simultaneously analyzed the SHGC and VT along with the economic effect. The purpose of this study is to analyze the possible combinations of SHGC and VT, and to quantify how the combinations affect energy consumption and economic feasibility. The comparisons of energy cost and initial investment cost are used to propose a guideline for selection of the economically-efficient exterior glazing for building. For analysis by building types, the analysis considers an office building for mostly-daytime operation, and a residential building for mostly-nighttime operation. The results of this study can be used as reference data to select economically-efficient building exterior glazing for four distinct seasons, because the combination of low SHGC and high VT is not always economically efficient. South Korea has four distinct seasons: it is hot and humid in the summer, but cold and dry in the winter.

This study is composed of two main steps (Fig. 1). First, the exterior glazing used in South Korea are investigated, and the possible combinations SHGC and VT are identified, then a sensitivity analysis of energy consumption is conducted for each combination. Next, the economic feasibility of actual glazing in terms of

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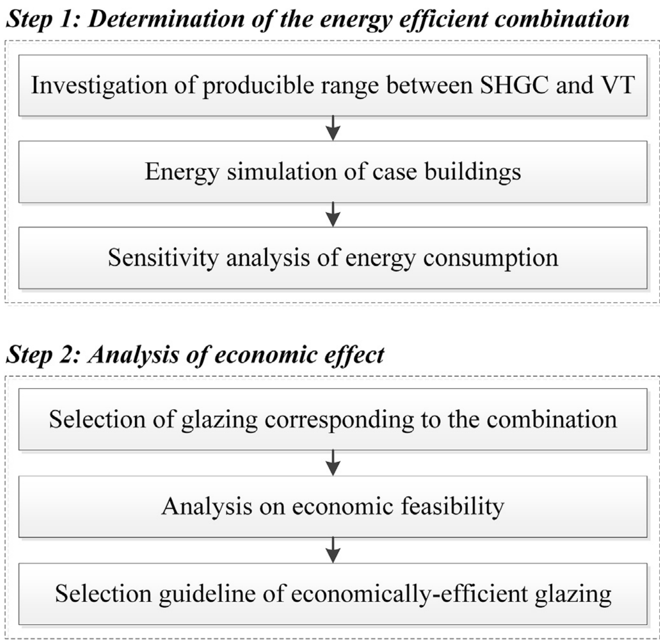

Fig. 1. Organization of research.

energy consumption that corresponds to the highest, median, and lowest energy combination is evaluated. The glazing costs, energy costs, CO_2 offset price, and real discount rate are included for economic feasibility. Lastly, to increase the economic efficiency of exterior glazing, a selection guideline is proposed by comparing energy cost and initial investment cost.

2. Literature review

Previous studies that analyzed the energy consumption and the economic feasibility depending on glazing types and properties can be classified as 1) analysis by climate type (Aguilar et al., 2017; Bouden, 2007; Yaşar and Kalfa, 2012); 2) analysis by orientation and building type (Jonsson and Roos, 2010; Lee et al., 2012; Singh and Garg, 2009; Urbikain and Sala, 2009); and 3) proposal of guidelines for energy management (Lee et al., 2013; Vanhoutteghem et al., 2015). Although the previous studies are similar to this study in that they analyze glazing types and glazing properties, the previous studies did not analyze the energy consumption and economic efficiency according to the trade-off relation between SHGC and VT. In addition, previous studies analyzed the glazing used in each country, and did not consider change of glazing properties. A sensitivity analysis of energy consumption depending on the combination of glazing properties could help a decision-maker to select economically-efficient glazing by comparing the energy cost and the initial investment cost.

Several previous studies were restricted to specific climate types. Aguilar et al. (2017) analyzed thermal efficiency based on double-glazed windows of four types (clear, absorbent, Low-e, and reflective) used in Mexico. Bouden (2007) conducted an energy analysis to select a curtain wall and glass suitable for the climate of Tunisia. Yaşar and Kalfa (2012) analyzed the energy consumption and conducted economic analysis for a high-rise building by type of double-glazed window; i.e., tinted glass, clear reflective glass, low emissivity glass, and smart glass (one surface consists of a high-reflectivity glass, and other surface has a low-emissivity coating).

Other previous studies analyzed efficiency based on types and orientation of building. Jonsson and Roos (2010) suggested a strategy to adjust the combination of windows, depending upon a balance of climate, building temperature, and building orientation. Lee et al. (2012) analyzed the energy consumption, CO_2 emission, economic analysis, and determined the suitable glazing type for each orientation of high-rise building. Singh and Garg (2009) analyzed heat energy in the Indian climate in terms of thermal transmittance and SHGC, building type and orientation, and climate. Urbikain and Sala (2009) analyzed energy efficiency in terms of the climate and building types for the window and window frame's thermal transmittance, absorptivity of the frame, SHGC, and infiltration.

Further studies proposed guidelines. Lee et al. (2013) proposed the chart for management of annual heating, cooling and lighting energy consumption according to glazing properties (thermal transmittance, SHGC, and visible transmittance), different window wall ratios, and orientations; the chart is intended to be used to guide selection of window systems for energy conservation. Vanhoutteghem et al. (2015) analyzed the relationship between size, orientation and glazing properties of façade windows, then presented the result as chart and proposed a method of combination to achieve minimum space heating, daylighting, and maximum thermal comfort.

Several of the previous studies were similar to this one, in that they analyzed the energy consumption and economic feasibility according to the combination of glazing properties, (Grynning et al., 2013; Kull et al., 2015). However, analysis in the previous studies was based on the change of thermal transmittance and SHGC, not on the trade-off between SHGC and VT. Grynning et al. (2013) analyzed impact by the combination of thermal transmittance and SHGC on energy consumption and proposed a method of rating an energy saving. Kull et al. (2015) derived five different glazing types based on various thermal transmittance and solar transmittance, and analyzed energy efficiency of windows.

This study analyzes energy consumption depending on the combination of SHGC and VT, then analyzes the effect of the combinations on economic feasibility in two types of building. The result enables comparisons of economic efficiency according to energy cost and initial investment cost and can therefore can be used to guide choices of building exterior glazing.

3. Basic settings for analysis

This section describes the input data required for analysis of energy consumption and economic feasibility. The major items include the range of glazing properties used on buildings in South Korea, characteristics of the buildings.

3.1. Possible combination of glazing properties

To determine the possible combinations of SHGC and VT, thermal transmittance was fixed, then the exterior glazing used in South Korea was investigated. The South Korean government recommends thermal transmittance $= 1.5$ W/(m^2·K) when windows are directly exposed to the outside (MOLIT et al., 2009). Among the glazings that have thermal transmittance <1.5 W/(m^2·K), the one with thermal transmittance $= 1.38$ W/(m^2·K) offers the widest range of glazing collections with various SHGC and VT values. Thus, in this study, thermal transmittance was set to 1.38 W/(m^2·K), then the available glazing products from three major glazing companies in South Korea were investigated. The three companies produce high energy efficient glazing products and import glazing products that they do not produce from the United States. SHGC $= 0.4$ and VT $= 0.74$ was the maximum considered, and SHGC $= 0.17$ and VT $= 0.14$ was the minimum (Table 1). In each combination, VT was decreased in increments of 0.1, because decrease of VT was not

Table 1
Possible combinations of glazing properties (thermal transmittance = 1.38 W/(m^2·K)).

SHGC	VT
0.40	0.74, 0.64, 0.54, 0.44, 0.34, 0.24, 0.14
0.32	0.61, 0.51
0.27	0.53, 43, 0.33, 0.23, 0.13
0.24	0.47, 0.37, 0.27, 0.17
0.19	0.24, 0.14

limited, but increase of VT was limited because of the trade-off relation between SHGC and VT.

Other basic settings for analysis of the combinations were as follows. First, glazing colors were not considered because the color is determined by the owner's preference and design trends. Use of double-glazing (24 mm thick; each pane 6 mm thick, air layer of 12 mm) was assumed because this type of glazing is the most popular in South Korea. Triple glazing was excluded because it is not common in South Korea, and even though the energy efficiency is better than double glazing, triple glazing is heavy and its production cost is high. Argon was assumed to be the gas injected between glazings (MOLIT, 2008). No glazing without argon met the requirement that thermal transmittance <1.5 W/(m^2·K). Lastly, other glazing properties were kept the same, except thermal transmittance, SHGC, and VT.

3.2. The simulation parameters of case buildings

For modeling and energy simulation, the QUick Energy Simulation Tool (eQUEST) 3-36 was used. eQuest 3-36 is a interacting building energy simulation tool that uses DOE-2 as the core simulation engine (Shrake et al., 2013). Two case buildings were chosen: an office building and a residential building, both in Seoul, South Korea. The energy consumption of the case buildings was strongly affected by the combination of glazing because they have a high rate of window in the building envelope.

The office building (Fig. 2a; Table 2) is oriented to the northeast, and is composed of 14 aboveground floors and 6 subterranean floors. The gross floor area is 588,884.8 m^2 and the window area is 10,671.66 m^2; percentages of wall area that was window were 95.8 on the southwest wall, 68.6% on the southeast, 85.1% on the northwest, and 95.9% on northeast (overall, 86.34% of wall area). Officially, the building operates from 5:00 a.m. to 7:00 p.m. on Monday, from 6:00 a.m. to 7:00 p.m. on Tuesday through Friday, and is closed on Saturday and Sunday. However, office workers often worked overtime and sometimes during weekends. The office space, including offices, a conference room, and a lobby, occupies about 79% of the total floor area.

The residential building (Fig. 2b; Table 2) is oriented to the north-northeast; it is composed of neighborhood facilities and communal spaces from the 1st to 4th floors, then building A is composed of residential spaces from the 5th to 51st floors, and

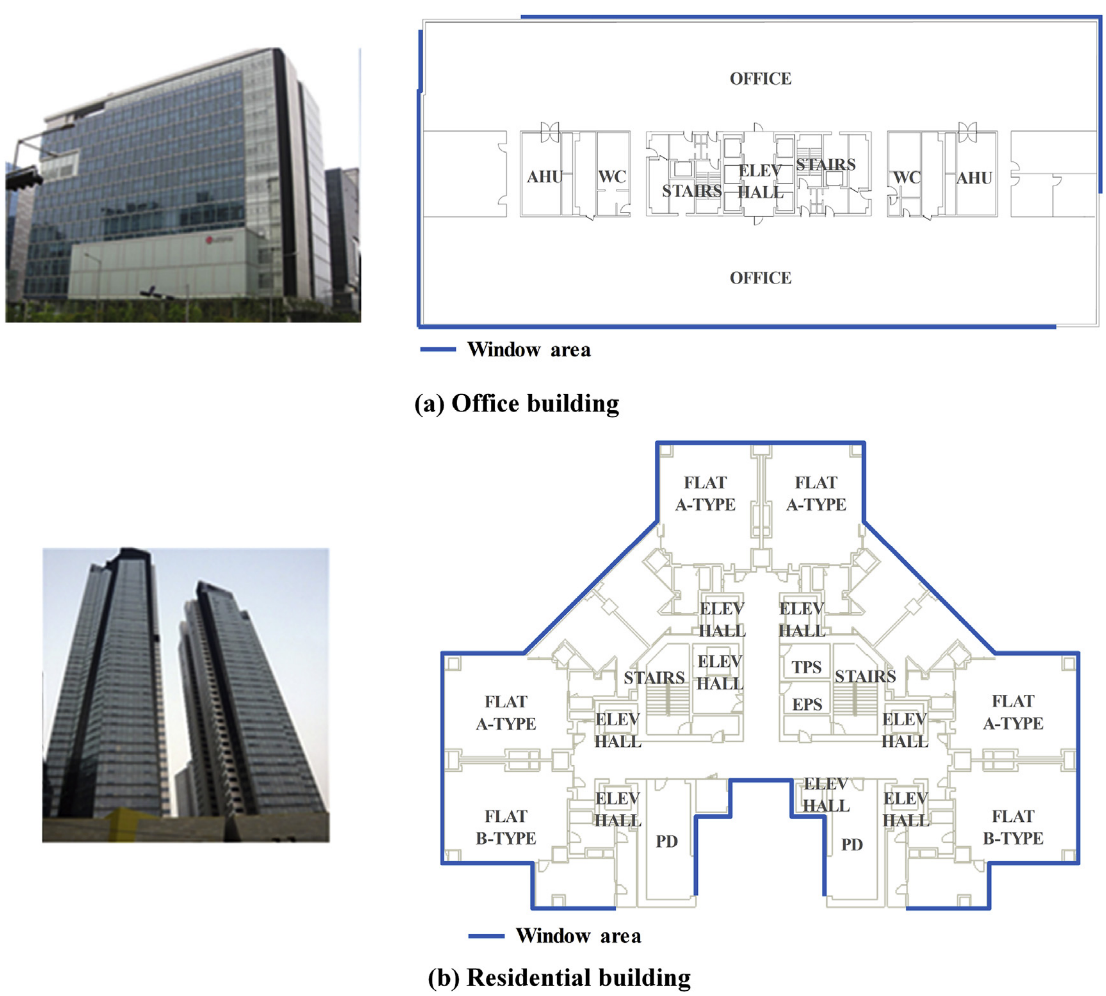

Fig. 2. Photographs and typical floor plans of the case building.

Table 2
Parameters of simulations for the case buildings.

Characteristic	Office building	Residential building
Orientation	North-East	North-North-East
The number of floors	14 + 6 subterranean	A: 46; B: 37
Gross floor area	58,884.80 m^2	105,100.24 m^2
Core area	8832.72 m^2 (15.00%)	37,933.49 m^2 (36.09%)
Wall area	12,360.60 m^2	48,256.36 m^2
Window area	10,671.66 m^2 (86.34%)	40,101.69 m^2 (89.17%)
Flr to Flr, Flr to Ceil	4.05 m, 2.40 m	3.30 m, 2.50 m
Schedules	Mon: 05:00–19:00, Tue - Fri: 06:00–19:00	24 h, typical residential building
Chiller type	Single stage absorption	Electric Reciprocating Hermetic
Boiler type	Condensing HW boiler	Condensing HW boiler

building B is composed of residential spaces from the 5th to 42nd floors. The residential space was considered, because the objective of this study is to analyze suitable glazing properties for office and residential buildings. The building is composed of 46 and 37 aboveground floors; the gross floor area is 105,100.24 m^2 and the window area 40,101.69 m^2; percentages of window were 95.8% on the southwest side, 68.6% on the southeast side, 85.1% on the northwest side, and 95.9% on the northeast side (overall, 89.17%). The building operates 24 h/d, as is typical of residential complexes.

4. Determination of the energy efficient combination

Energy consumption was quantified for each combination of glazing properties (Table 1). For the office building, energy consumption was lowest for SHGC = 0.19, and VT = 0.24 (Fig. 3). SHGC strongly affected the energy consumption because the office building was used primarily during daytime. Thus, low SHGC is equivalent to low energy consumption. However, the energy consumption of the combination (SHGC = 0.27, VT = 0.53 or 0.43) is lower than the combination (SHGC = 0.24, VT = 0.17) because the increased lighting energy by low VT is larger than decreased cooling and HVAC by low SHGC. This result is similar to the case

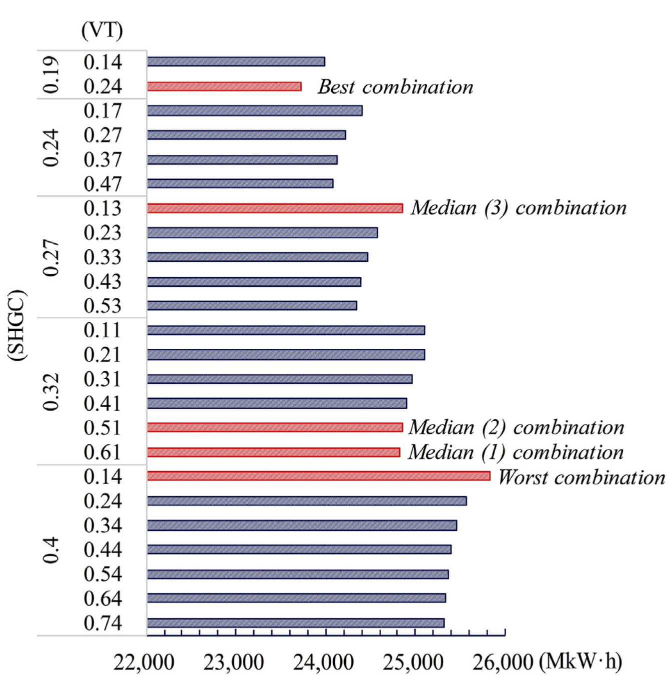

Fig. 3. The energy consumption of the case office building.

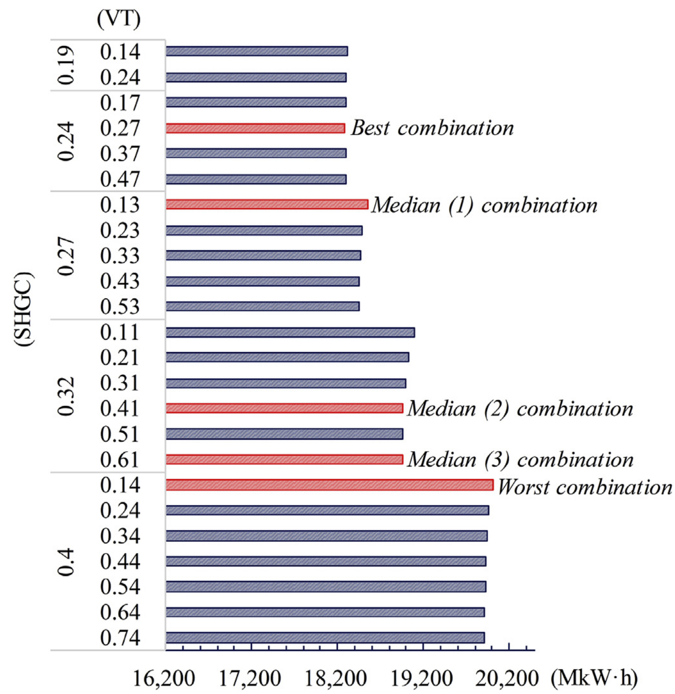

Fig. 4. The energy consumption of the case residential building.

that the energy consumption of combination (SHGC = 0.32, VT = 0.61) is lower than the combination (SHGC = 0.27, VT = 0.13). Thus, a highly energy-efficient glazing can be selected if the decision-maker refers to the combination not only one properties strongly affect energy consumption.

For the residential building, the combination of the lowest energy consumption was SHGC = 0.24 and VT = 0.27 (Fig. 4). Generally, the lighting energy is decreased by high VT but the energy consumption of SHGC = 0.24 and VT = 0.27 is lower than SHGC = 0.24 and VT = 0.47. The reason that consumption of gas and HAVC for heating is increased more than decreased electricity consumption by decreased lighting use. The heating energy has a stronger effect than other energy because the residential building is mainly used at night. Similar results were obtained for the scenarios SHGC = 0.27 and VT = 0.53 or 0.43, and SHGC = 0.32, VT = 0.61 or 0.41. Thus, if decision-maker uses the result, an excessively high energy efficient glazing would not be selected because its investment cost generally excessive. The energy efficiency by glazing combination can be used as a reference for selecting combinations when the initial investment cost is constrained.

Sensitivity analysis was used to compare the energy efficiency of given combinations in different building types. In the office building, the energy consumption is mostly low if SHGC is low but VT is high. However, in the residential building, the energy efficiency of high SHGC and low VT glazing is not always high and the rank of energy efficiency did not change linearly. Thus, the result of the sensitivity analysis is more useful when applied to residential buildings than to office buildings.

5. Analysis of economic efficiency of buildings

In this section, based on the energy consumption of the combinations (Figs. 3 and 4), economic feasibility was assessed for the combinations that had the highest, median, and lowest energy efficiency, then a guideline for selection of economically-efficient

Table 3
Unit prices of energy sources.

Category		Unit cost ($US/(MkW·h))	CO_2 emission (tCO_2eq)	CO_2 offsets price ($US)
Hot water for heating		98.59	0.000160	22.73
Gas (LNG)		53.37	0.002231	
Chilled water for cooling	Jul–Aug	134.45	0.000136	
	Jan–Jun, Sep–Dec	70.15		
Electricity	Jul–Aug	109.01	0.00047	
	Mar–Jun, Sep–Oct	76.19		
	Nov–Dec	103.98		

* Using exchange rate $US 1 = KRW 1139.7 as of April 22, 2017.

glazing was proposed. The factors considered include the initial cost of the glazing (price per square meter), and the energy cost and CO_2 offset price of each type of glazing. Labor costs, shipping costs, maintenance costs, and salvage costs are included in the initial sales price, and therefore are assumed to be the same for all glazing types. The economic feasibility was analyzed for 10 years, which is the general warranty period of U.S. glazing manufacturers (U.S. Department of Energy by the Pacific Northwest National Laboratory, 1998); and for 40 years, which is the general service life of buildings as set in the enforcement regulations of South Korea's tax law (Integrated Legislation Knowledge Management System, 2009).

For heating and cooling (Table 3), the office building uses hot water and chilled water at Korea District Heating Corporation (KDHC) rates (2017). The KDHC uses landfill gas as the energy source. The residential building uses liquefied natural gas (LNG) of Seoul City Gas Company Limited rate (2017) and electricity of the Korea Electric Power Corporation rate (2017). The electricity is also used for lighting for both case buildings. In South Korea, greenhouse gas emission-trading was started on January 2015 by the Korea Exchange; this study applied a price of February 2017 (US$22.73/$tCO_2eq$) (Greenhouse Gas Information Center, 2017). A real discount rate for economic feasibility was applied based on Eq. (1) (Lee and Lee, 2017) using provided consumer price index f and nominal interest rate i by The bank of Korea (2017):

$$i = \frac{1 + in}{1 + f} - 1. \tag{1}$$

First, based on analyzed combination of SHGC and VT, the glazing was selected for use in the office building (Table 4). If the glazing corresponding to the combination is used in South Korea, the glazing was selected; if not, the most similar glazing was selected. In analysis of energy consumption (Fig. 3), the glazings that correspond to the worst and median combinations are used in South Korea but the best combination glazing (SHGC = 0.19, VT = 0.24) is not. Thus, the nearest glazing used in South Korea (SHGC = 0.18, VT = 0.18) was selected as the best combination.

The economic feasibility analysis (Fig. 5) suggests that the break-even point was reached in five years although the initial investment cost of the median and best combination is higher than the worst combination. After ten years, the median and best combination can reduce the cost by $US 554,292 and $US 950,036, respectively in comparison with the worst combination; these reduced costs are ~50% and ~80% of initial investment, respectively. After 40 years, the median and best combination can reduce the cost by $US 2,069,142 and $US 3,499,053, respectively in comparison with the worst combination; these are about two and three times the initial investment cost, respectively. Thus, the best combination of SHCG and VT had high economic efficiency for the office building.

Next, economic feasibility was conducted for glazings of the residential building (Table 5). The worst and median combinations of glazing were the same as in the office building but the best combination was not. The best combination is used in South Korea, so this glazing was selected.

Break-even also occurred after five years (Fig. 6), as for the office building, although investment costs of median and best combination were larger than the worst combination. After ten years, the

Table 4
Cost of selected glazing for a case office building (thermal transmittance = 1.38 W/(m^2·K)).

Combination	SHGC	VT	Unit cost ($US/$m^2$)	Construction cost ($US)
Worst	0.40	0.74	86.3	921,371.43
Median	0.27	0.42	97.7	1,043,101.36
Best	0.18	0.18	103.9	1,108,608.12

* Using exchange rate $US 1 = KRW 1139.7 as of April 22, 2017.

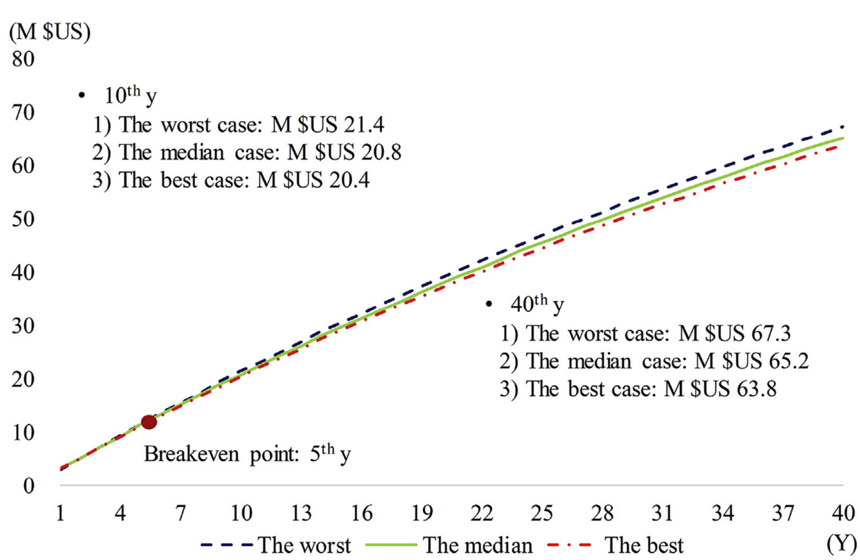

Fig. 5. The economic feasibility of the office building.

Table 5
Cost of selected glazing for a case residential building (thermal transmittance = 1.38 W/(m^2·K)).

Combination	SHGC	VT	Unit cost ($US/$m^2$)	Construction cost ($US)
Worst	0.40	0.74	86.3	3,715,134.61
Median	0.27	0.42	97.7	4,205,971.48
Best	0.24	0.27	100.9	4,341,891.57

* Using exchange rate $US 1 = KRW 1139.7 as of April 22, 2017.

median and best combination can reduce costs by ~$US 626,333 and ~$US 671,040 compared to the worst combination. These are equivalent to both about 15% of initial investment cost. After forty years, the median and best combination can reduce cost by ~$US 3,120,090 and $US 3,566,117, which are equivalent to ~74% and 82%, respectively. These results suggest that for the residential building, the economic efficiency of the best glazing is lower than for the office building, although investment cost is higher than for the median glazing.

Lastly, the best glazing for office building was applied to the residential building and vice versa, and the results of economic feasibility were compared (Fig. 7, Fig. 8). The purpose of this procedure is to analyze the applicability of different combinations to buildings of different type. When both the best glazings for residential and office buildings were applied to the residential building (Fig. 7), the difference of energy consumption between case buildings was small, but the initial investment cost of the best combination was ~$US 128,215 higher for the office building than for the residential building. However, the difference of the energy consumption is increased steadily when the best glazings were applied to the office building; the result means that the economic efficiency of high SHGC and low VT glazings differs by building type. Thus, the findings of this study can be applied as reference data to determine the economic efficiencies of combinations for different building types. Especially, this study can contribute to the efficiency of limited investment cost by comparing the decrease in energy cost and increase in initial investment cost depending on the combination.

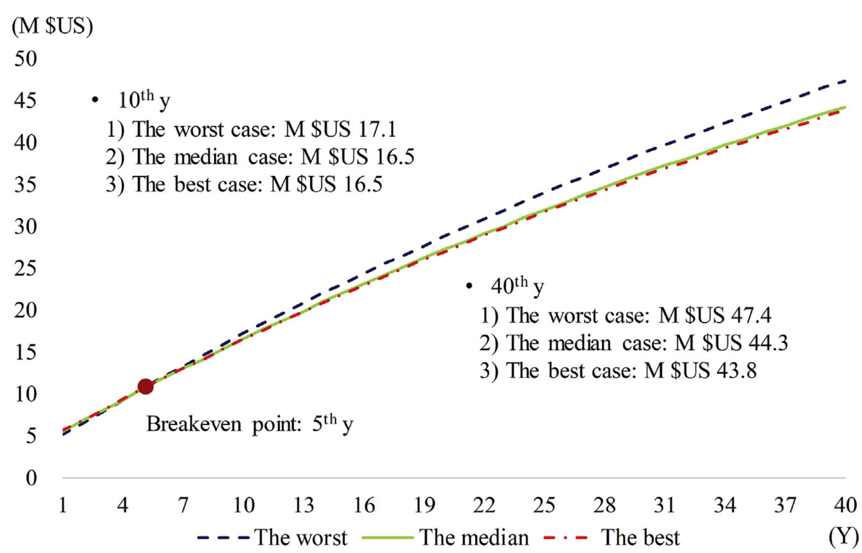

Fig. 6. The economic feasibility of the residential building.

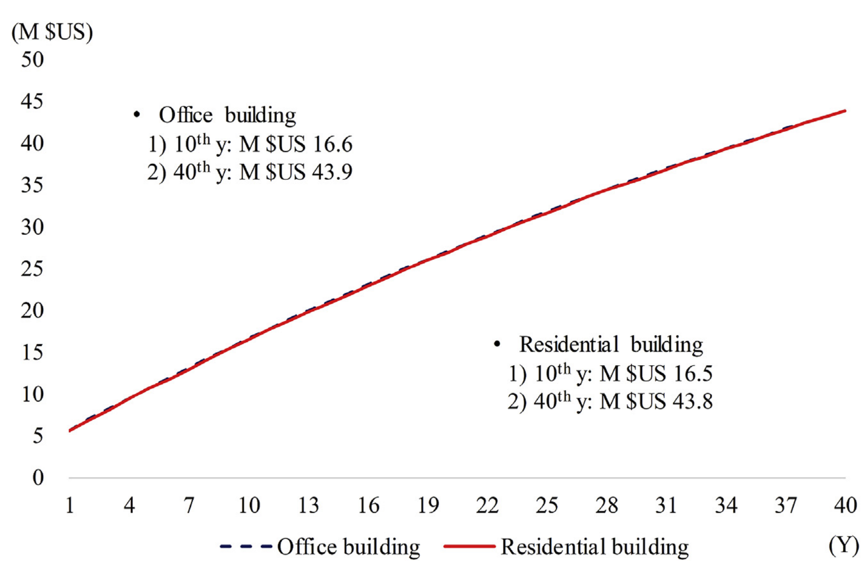

Fig. 7. The comparison between best glazings for residential building.

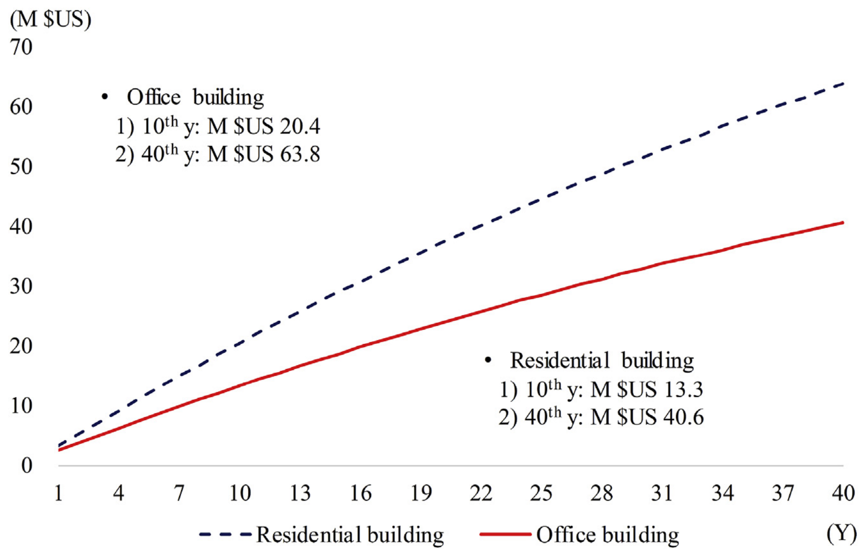

Fig. 8. The comparison between best glazings for office building.

6. Conclusions

Appropriate choice of energy-efficient glazing is critical because heat loss from windows is about 20% of total heat loss (Oleskowicz-Popiel and Sobczak, 2014). Especially, the combination of glazing properties is important in South Korea because it has four distinct seasons and relatively long summers and winters. Although selecting the glazing by the combination of low SHGC and high VT is important to reduce the energy consumption, the development of the glazing is limited by a trade-off relationship between SHGC and VT (Fathoni et al., 2016). Previous studies did not consider the combination of SHGC and VT when they analyzed the energy consumption and economic efficiency. This study analyzed how the combination of glazing properties (SHGC and VT) affects the energy consumption of an office and a residential building in South Korea, and analyzed the economic feasibility of each combination. Then, a guideline to improve the economic efficiency was proposed.

First, building exterior glazings used in South Korea were investigated, and possible combinations of SHGC and VT were identified. Then the energy consumption of each combination was analyzed. As glazing efficiency increased (e.g., low SHGC and high VT), energy consumption tended to decrease the office building, but not in the residential building. Thus, application of the energy consumption by combination is more useful for residential buildings than for office buildings. Next, the economic feasibility was analyzed for each combination and compared by building type. Although the median and best combinations had higher initial investment cost than the worst combination, they reduced energy consumption, so overall costs were the same after five years and lower. Ultimately, the initial investment would be repaid about three times.

For the office building, the economic efficiency can be improved if the decision-maker considers energy consumption rather than investment cost, because energy consumption is large and energy consumption decreased linearly as glazing efficiency increases. For residential buildings, if the weighting is given to the investment cost when the inflection point of the energy consumption was passed, the economic efficiency can be improved; i.e., if the combination of exterior glazing is selected based on comparison of increase in investment cost to decrease in energy cost, the economic efficiency can be improved. The findings of this study can be used to support decision-making as reference data for selection of building exterior glazing, because the most energy-efficient combination of glazing properties is not always the most economically-efficient.

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